

The Combustion Experiments on the Mir

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Almost everything about fires is changed in microgravity, and many of the differences are counter-intuitive. Some examples: microgravity fires may spread faster upstream than downstream, opposite to the behavior seen on earth. While fire in space is often weaker than on earth, more inert may be needed for extinguishment. Turbulent flames, commonly thought to be completely independent of gravitational influence, have been seen to double in size when tested in weightlessness. As Prof. Gerard Faeth of the University of Michigan has said, these findings show that gravity has impeded the rational development of combustion science in much the same way that the atmosphere has impeded astronomy.

Combustion processes on earth naturally generate buoyant flow (i.e. light gases rising) that dominates mass and heat transport. In microgravity, transport is primarily by molecular diffusion or by fan-driven convection. The net result: certain materials considered non-flammable on earth can become flammable in microgravity, for example when low-speed air flows, *at velocities below those induced by buoyancy on earth*, are provided by ventilation systems. Without this air flow, thermal radiation in microgravity is often (but not always) a heat loss that cools the combustion process to the extent that

the fire stops producing any smoke and may even self-extinguish. Thus the first (but not sole) line of defense against ongoing fires in spacecraft is to turn off all local power and ventilation, and wait until heat loss and the diminished rate of reactant transport eliminate the fire.

The nature of smoke (soot emitted from a fire) is also different, because buoyancy on earth rapidly accelerates the soot through the flame. In microgravity reactant flow rates can be controlled to yield prodigious amounts of soot and large aggregates of particulate. Recent Shuttle experiments began to map soot production processes as the particulate moved slowly along tractable pathlines; the data suggest the existence of universal relationships known as the soot paradigm, a controversial hypothesis that, if proven, will be used to model and control many practical combustion systems on earth. These data apply to the astronauts' fire safety as well. Smoke detectors on the Shuttle and the International Space Station (ISS) are sensitive to the amounts and types of soot produced. The sensitivity of the detectors to particulate produced by a material burning on earth is not an indication of its sensitivity to the particulate produced by the same material burning in weightlessness.

The first experiments Dr. Lucid performed on Mir were conceived as an inexpensive way to characterize the Mir for future microgravity combustion experiments, and to determine whether a flame supplied with reactants by diffusion, like that produced by a candle, would be sustainable in microgravity. Both answers were positive: candles that burn for 10 minutes or less on earth produced a flame for up to 45 minutes on the Mir. After a period of time (see Figure 1), the flame became quite weak and all blue (too cold to produce yellow, luminous soot), so weak that all the video cameras onboard

lacked the sensitivity to see them. Dr. Lucid however observed them by peeking into the chamber, and then used still photography, audio recordings and on-the-spot sketches to capture the flame and related surprising phenomena – rapid, expansive melting of the wax despite the weakness of the flame, large-scale swirling flow in the liquid ball and its subsequent and sudden collapse, issuance of wax droplets through the quench layer under the flame (see Figure 2), and tens-to-hundreds of spontaneous, low-frequency flame oscillations before the flame extinguished, unlike anything seen or predicted to date. Finally, when she switched the chamber lights on after the flame extinguished, the biggest surprise was the appearance of a white ball (see Figure 1d) surrounding the candle tip. The ball is believed to be a fog of droplets that formed after flame extinction, when wax vapor still issuing from the hot wick and ambient water vapor condensed in the colder air. The formation of a flammable cloud served as an excellent reminder regarding fire safety in spacecraft: the hazardous event is not ended when the fire extinguishes because flammable material can continue for some time to issue from the source of the fire. Also, smoke detectors would be unable to sense these kinds of weak, non-smoking flames (but they are so weak as to be non-hazardous).

Dr. Lucid and Dr. Jerry Linenger performed additional experiments on the Mir involving the burning of plastic and cellulosic materials. These were conducted in a low-speed wind tunnel that, like all the combustion hardware, was built at NASA's Glenn Research Center in Cleveland, Ohio. The experiments focused on the type and thickness of the flammable material and the direction and speed of fan-driven convection. Opposed airflow (upwind) and concurrent airflow (downwind) flame spread was studied, as well as the shape of the fuel sample (e.g. solid and hollow cylinders, sheets).

Polyethylene cylinders were heated to between 85 and 100 C prior to ignition by resistance heating the wire core. As the flame spread, the fuel melted and flowed into a transparent ellipsoidal bead. In each case, the molten fuel bead grew during flame spreading and remained inside the flame. As the beads of molten fuel grew, fuel vapor bubbles gradually form then burst, releasing small jets of fuel vapor that briefly distort the flame (seen in the images as a random fluctuation in the flame shape). Bursting bubbles also ejected small flaming particles that were carried downstream. When the flame reached the end of the fuel sample, its behavior was completely dominated by the formation and bursting of fuel vapor bubbles. In each case, the fuel was completely consumed by the flame. In normal gravity tests, melting fuel flows or drips down toward the ground, exiting the flame zone. In contrast to the tests with cellulose samples (described below), soot was emitted from the flames in very long or continuous agglomerate threads. Earlier tests of this type conducted aboard the Space Shuttle¹¹ showed similar long threads and primary particles slightly larger than soot primaries collected from identical samples in normal gravity. Normal gravity flame spread behavior of identical fuel samples is quite different than these Mir results. In addition to the removal of significant fuel from the flame by dripping, buoyant airflow carries soot quickly through the flame, preventing the extended growth of soot agglomerates.

A series of cellulosic paper samples were also tested. For paper sheets and small diameter paper cylinders, the flames were dim and blue. The spread rate more than doubled as the airflow speed was increased from 3 to 5 cm/s. This is completely different from the trend in normal gravity where increasing the airflow may *decrease* the spread rate, and suggests the importance of the flow to the material flammability. The only large

diameter sample that was burned had a partially hollow core. The intention of this test was to seek a flow velocity at which the air flow was insufficient to sustain the flame. The sample was ignited at a relatively high flow velocity (9 cm/s), but as hoped the flame went out as the velocity was subsequently reduced to approximately 5 cm/sec.

To summarize: in the range of low-speed flows tested, increasing the flow rate caused the flames to strengthen significantly. When the forced air flow was stopped, the flames self-extinguished. This provided a simple and successful test of the spacecraft safety practice (described earlier) to immediately eliminate all ventilation upon the occurrence of a fire. Such action can often suppress the fire without the need to resort to a fire extinguisher or venting to the vacuum of space. It may also prevent the spread of smoke to regions of the spacecraft far from the fire. In contrast, the candle flames persisted in a quiescent environment. Similar to candles, droplet combustion persists in quiescent environments, as do other combustion systems. While extinguishment in space is certainly promoted when ventilation is stopped, it is not always certain that this method will be 100% effective in isolation. Thus active fire extinguishers remain necessary to be incorporated into a complete fire safety strategy for spacecraft.

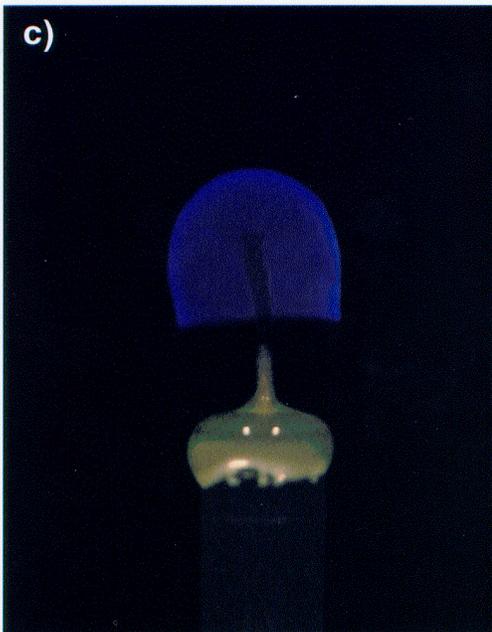
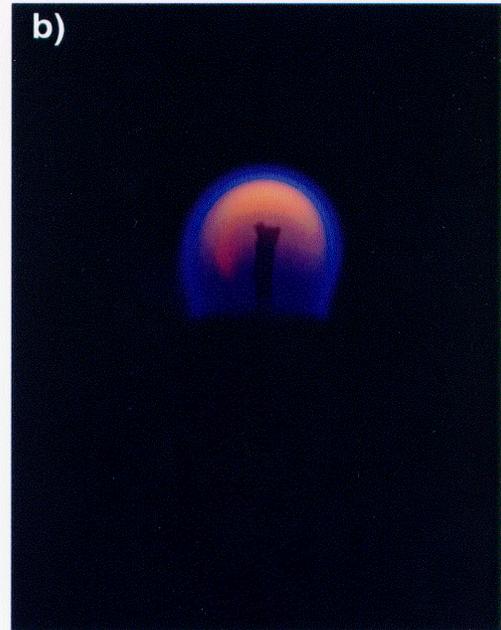
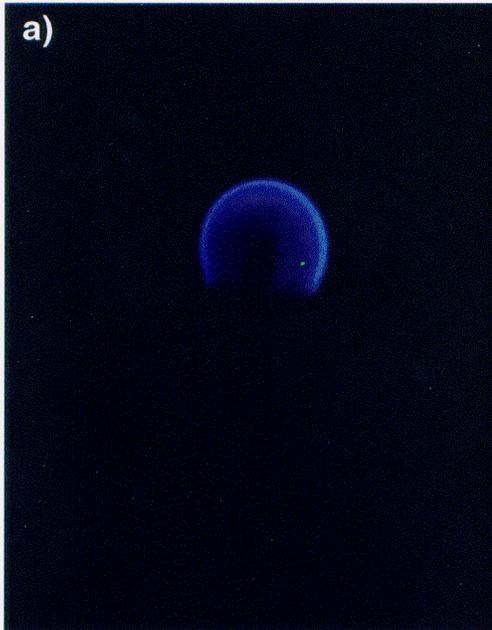
From a scientific perspective, the microgravity experiments provided evidence of the importance of radiation for controlling these flames. Though on earth it is usually considered important only for large fires, radiation plays an important role in microgravity even if the flame is small. This finding is based both on the experimental behavior and by an associated modeling effort, and is applicable only when the complicating effects of buoyancy are not present.

Low-speed air flow, 'self-generated' gas flow, molten fuel effects, large scale thermocapillary effects, vapor 'cloud' generation, and flaming ejected particles were all seen. Many of these effects were unexpected, and all have important application to spacecraft fire safety, and demonstrate the need to analyze flammability risks on a case-by-case basis.

Figure 1: The shape of the candle flame (a) early in flame lifetime; (b) just after the wax melts completely; (c) just after the molten ball collapses; and (d) spherical fog of wax droplets after flame extinction (*reprinted from Dietrich et al, 2000*).

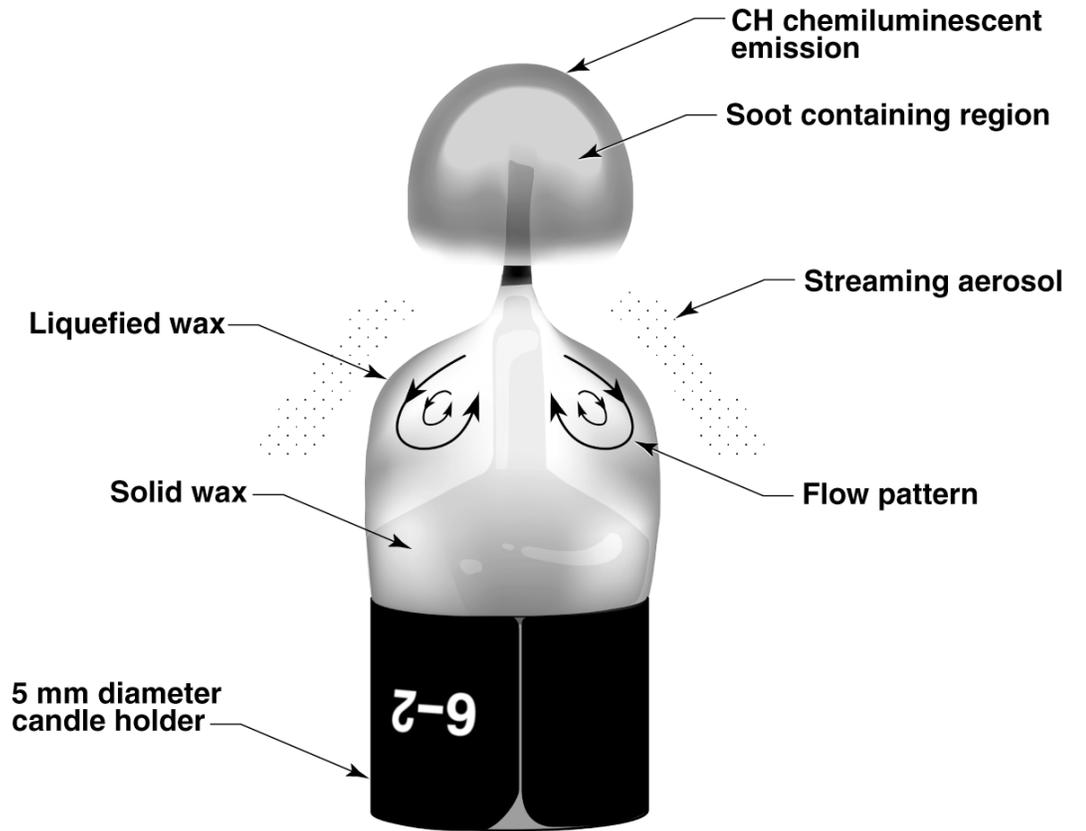
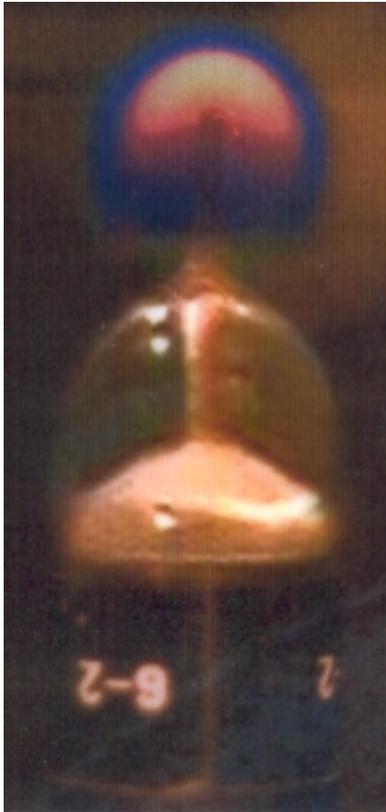


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Figure 2: Liquefied wax shape during melting of 5 mm candle within the first minutes of candle burning in microgravity.



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